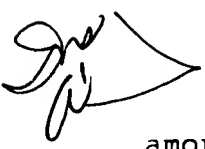


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SALINE SOLUBLE INORGANIC FIBRES



This invention relates to saline soluble, non-metallic, amorphous, inorganic oxide, refractory fibrous materials.

Inorganic fibrous materials are well known and widely used for many purposes (e.g. as thermal or acoustic insulation in bulk, mat, or blanket form, as vacuum-formed shapes, as vacuum formed boards and papers, and as ropes, yarns or textiles; as a reinforcing fibre for building materials; as a constituent of brake blocks for vehicles). In most of these applications the properties for which inorganic fibrous materials are used require resistance to heat, and often resistance to aggressive chemical environments.

Inorganic fibrous materials can be either glassy or crystalline. Asbestos is an inorganic fibrous material one form of which has been strongly implicated in respiratory disease.

It is still not clear what the causative mechanism is that relates some asbestos with disease but some researchers believe that the mechanism is mechanical and size related. Asbestos of a critical size can pierce cells in the body and so, through long and repeated cell injury, have a bad effect on health.

Whether this mechanism is true or not regulatory agencies have indicated a desire to categorise any inorganic fibre product that has a respiratory fraction as 'hazardous', regardless of whether there is any evidence to support such categorisation. Unfortunately for many of the applications for which inorganic fibres are used, there are no realistic substitutes.

Accordingly there is a demand for inorganic fibres that will pose as little risk as possible (if any) and for which there are objective grounds to believe them safe.

A line of study has proposed that if inorganic fibres were made that were sufficiently soluble in physiological fluids that their residence time in the human body was short; then damage would not occur or at least be minimised. As the risk of asbestos-linked disease appears to depend very much on the length of exposure this idea appears reasonable. Asbestos is extremely insoluble.

As intercellular fluid is saline in nature the importance of fibre solubility in saline solution has long been recognised. If fibres are soluble in physiological saline solution then, provided the dissolved components are not toxic, the fibres should be safer than fibres which are not so soluble. The shorter the time a fibre is resident in the body the less damage it can do. H. Förster in 'The behaviour of mineral fibres in physiological solutions' (*Proceedings of 1982 WHO IARC Conference, Copenhagen, Volume 2, pages 27-55(1988)*) discussed the behaviour of commercially produced mineral fibres in physiological saline solutions. Fibres of widely varying solubility were discussed.

International Patent Application No. WO87/05007 disclosed that fibres comprising magnesia, silica, calcia and less than 10 wt% alumina are soluble in saline solution. The solubilities of the fibres disclosed were in terms of parts per million of silicon (extracted from the silica-containing material of the fibre) present in a saline solution after 5 hours of exposure. The highest value revealed in the examples had a silicon level of 67 ppm. In contrast, and adjusted to the same regime of measurement, the highest level disclosed in the Förster paper was equivalent to approximately 1 ppm. Conversely if the highest value revealed in the International Patent Application was converted to the same measurement

regime as the Förster paper it would have an extraction rate of 901,500 mg Si/kg fibre - i.e. some 69 times higher than any of the fibres Förster tested, and the fibres that had the highest extraction rate in the Förster test were glass fibres which had high alkali contents and so would have a low melting point. This is convincingly better performance even taking into account factors such as differences in test solutions and duration of experiment.

International Patent Application No. WO89/12032 disclosed additional fibres soluble in saline solution and discusses some of the constituents that may be present in such fibres.

European Patent Application No. 0399320 disclosed glass fibres having a high physiological solubility.

Further patent specifications disclosing selection of fibres for their saline solubility are European 0412878 and 0459897, French 2662687 and 2662688, PCT WO86/04807 and WO90/02713.

The refractoriness of the fibres disclosed in these various prior art documents varies considerable. The maximum service temperature of any of these disclosed fibres (when used as refractory insulation) is up to 815°C (1500°F).

Service temperature for refractory insulation is definable in many ways but to be consistent with the above mentioned International Patent Applications this application shall mean by service temperature that temperature at which the fibre shows acceptable shrinkage (maximum of 5% linear shrinkage after exposure to temperature for 24 hours) and at which the fibre has not appreciably suffered through excessive sintering or softening.

There is a demand for physiologically soluble fibres having a service temperature of greater than 815°C,

particularly for such fibres having a service temperature above 900°C.

Testing for physiological solubility and safety can be done by inhalation studies on, e.g. rats. However such studies are extremely time consuming and costly. A study can take of the order of 2½ years from start and can easily cost £1 million per study. A cheaper alternative is to test for solubility in physiological or like fluids *in vitro*.

Testing of an inorganic fibre for solubility in physiological solutions is not so time consuming, but there is currently no way of predicting which systems will produce such soluble fibres. Therefore anyone seeking to find such soluble fibres has to work on a trial and error basis assisted by what is commonly known as 'chemical intuition' but is equally commonly known as 'a hunch'. Such trial and error testing is laborious and time consuming. Further, once a fibre is found that is soluble there is no guarantee that it will be usable at useful service temperatures.

Accordingly there is a demand for a method of predicting whether a fibre will have a reasonable solubility in physiological solutions, and further there is a demand that such a test should preferably give an indication as to expected service temperature.

Shrinkage of inorganic refractory fibres occurs through two mechanisms; the first is viscous flow of the fibre material. Most inorganic refractory fibres are glasses and so may be defined as liquids having an exceedingly high viscosity (but still liable to flow). By their nature fibres are elongate and so have a high surface area per unit volume. As the reduction of surface area is a means of reducing the surface energy of a material, when the glass becomes fluid enough it will flow so as to reduce surface area. This flow results in a coarsening and shortening of the fibres and so to

shrinkage, and in the extreme results in disruption of the fibres into separate particles.

The second mechanism leading to shrinkage is that at elevated temperatures glasses may crystallise to form one or more crystal phases. Usually these crystal phases have a smaller molar volume than the glasses from which they crystallise and so shrinkage results. Some fibres are known for which the molar volume of the crystalline form exceeds that of the glass (for example $\text{Al}_2\text{O}_3/\text{SiO}_2$ glassy fibres may crystallise to form mullite crystals). In these cases the expansion due to crystallisation may oppose the shrinkage caused by viscous flow.

If shrinkage through viscous flow occurs at a much lower temperature than crystallisation then the crystallisation may not be able to compensate for such shrinkage.

There is a demand for a fibre in which both viscous flow and crystallisation occur at as high and as similar a temperature as possible, and preferably in which the expansion due to crystallisation closely matches the shrinkage due to viscous flow so that the net effect is as close to zero shrinkage as possible.

When used as refractory insulation inorganic refractory fibres are used in several forms. The fibres may be supplied as a bulk material, but in this form the fibres are difficult to handle for many applications. Alternatively the fibre may be supplied as a blanket. Blanket fibre is generally made by a process of sucking fibre from air onto a conveyor to form a blanket. Because the fibres tend to be aligned parallel to the conveyor surface they can separate easily. Accordingly the blanket fibres are secured together by adding a binder to lock the fibres together, or by needling the blanket, or both. In needling needles are passed through the thickness of the blanket to push and draw fibres to lie transverse to the

blanket and so tie the fibres together. Because binders are usually resins, such as phenolic resins, they burn off on first firing. There is a desire to reduce the amount of such binders used both because of possible health implications in handling, and because the combustion products may affect the strength of the fibres. Thus needled blanket is usually preferred.

The fibres may also be supplied as blocks, generally made from assembled layers of inorganic fibre blanket.

For some fibres needling is not possible. Crystalline fibres are generally too brittle to stand the stresses involved. For the fibres known in the industry as glass fibres (which are generally used for low temperature applications) the amount of 'shot' (unfiberised glass particles) present is generally too high to allow needling as the shot damages the needles. There is no needled blanket on the market that has a maximum service temperature in the range 900°C-1200°C. There are needled blankets having a higher maximum service temperature but these use expensive fibres in comparison with other fibres usable (with the aid of binders) as blanket in the temperature range 900°C-1200°C.

Accordingly there is a demand for needled fibre blanket formed from inexpensive materials, being soluble in saline solutions, and having a maximum service temperature in the range 900°C-1200°C.

As stated previously refractory oxide fibres are made by several methods all of which involve the formation of a melt of oxides and the subsequent fiberisation of the melt by e.g. spinning or blowing.

The melt of oxide material is often formed by electrical discharge melting of the constituent raw materials. The applicants, in manufacture of a CaO/MgO/SiO₂ refractory oxide

fibre encountered problems due to the necessity of handling CaO. These problems were discovered to be due to the moisture content of CaO as commercially available. One of the problems of use of CaO is the outgasing that results upon melting and this led at the least to a porous melt pool which caused fluctuations in the melt current; in the extreme the outgasing was explosive. Additionally use of CaO appeared to cause accelerated attack on the melt electrodes. Also CaO is a difficult and corrosive material to handle.

Accordingly there is a need for a process that minimises the use of CaO.

Accordingly the present invention provides the following features both independently and in combination:-

A. Use of a vitreous inorganic fibre in the knowledge that it has a composition meeting the criteria either:- that the calculated sum of the free energies of hydration of the compounds that would or could be present at equilibrium (on the basis of knowledge, informed belief or reasonable assumption) is more negative than -10 kcal/100grams (-418.4kJ/kg) of composition; or that the percentage of non-bridging oxygens is more than 30%. Such compositions tend to be saline soluble.

B. Use of such a vitreous inorganic fibre in the knowledge that it has a composition meeting the criterion that the ratio of glass modifiers to network formers is less than a critical value (for SiO₂ based compositions the critical value is 1). Such compositions tend to be glass formers.

C. The invention also encompasses fibres selected by adopting such criteria as a test for solubility and glass formation.

D. Use as saline soluble fibres having a shrinkage of less

than 3.5% when exposed to 1000°C for 24 hours and/or 800°C for 24 hours, of vitreous fibres having a composition comprising (in weight %):-

SiO ₂	>58%	- (for MgO =< 10%) and
SiO ₂	>58% + 0.5(%MgO -10)	- (for MgO >= 10%)
(SiO ₂ preferably being below 70%)		
CaO	0% - 42%	
MgO	0% - 31.33%	
Al ₂ O ₃	0% - <3.97%	

and being essentially free of fluxing components such as alkali metals and boron oxide.

E. In one such usage the first crystalline material resulting on crystallisation has the crystal structure of diopside and has the composition consisting essentially of:-

<u>Component</u>	<u>Composition A</u>
	<u>Weight percent</u>
SiO ₂	59-64
Al ₂ O ₃	0-3.5
CaO	19-23
MgO	14-17

F. In a second such usage the first crystalline material resulting on crystallisation has the crystal structure of wollastonite/pseudowollastonite and has the composition consisting essentially of:-

<u>Component</u>	<u>Composition B</u>
	<u>Weight percent</u>
SiO ₂	60-67
Al ₂ O ₃	0-3.5
CaO	26-35
MgO	4-6

G. The fibres used in such manner may further be used as needled blankets.

H. Preferably the fibres of the general composition and compositions A and B mentioned above have a SiO₂ content (expressed as a weight percentage of the constituents SiO₂, CaO and MgO) of greater than 60%.

I. The present invention further provides a method for the manufacture of refractory oxide fibres containing calcium and silicon by the formation of an oxide melt containing calcium and silicon characterised in that all or part of the calcium and all or part of silicon is provided by a calcium silicate.

The invention is illustrated by way of example in the following description and with reference to the drawings in which:-

Fig.1 is a three-axis phase diagram indicating the crystalline phases in the system SiO₂/CaO/MgO (*Phase Diagrams for Ceramists*, The American Ceramic Society, 1964) a key to this diagram is at the end of the specification;

Fig.2 is a three-axis composition plot of the projection onto the SiO₂/CaO/MgO phase field of compositions comprising SiO₂, CaO, MgO and Al₂O₃;

Fig.3 is a temperature/time plot of the firing regime used in a series of cyclic exposure tests of experimental

compositions;

Fig.4 is a plot of log (total solubility) v calculated free energy of hydration for a series of fibres.

Fig.5 is a plot of log (total solubility) v % non-bonding oxygens for a series of fibres (see below).

A series of fibres were made of the compositions shown in Table 1. These fibres were melt spun by using a vertical spinning system of the type known for making inorganic fibres. Also shown in Table 1 are the compositions of some comparative commercially available inorganic oxide fibres and glass fibres.

TABLE 1

	Al ₂ O ₃	SiO ₂	CaO	MgO	ZrO ₂	
SW-A	3.3	59.3	20.5	15.5	-	
SW-A1	1.1	63.7	20.5	15.2	-	
SW-A2	0.8	60.8	21.4	15.4	-	
SW-B1	2.3	65.3	26.8	5.7	-	
SW-B2	1.3	66.9	27.5	5.2	-	
SW-B3	1.0	60.0	34.0	4.4	-	

COMPARATIVE EXAMPLES

	Al ₂ O ₃	SiO ₂	CaO	MgO	ZrO ₂	MST
CRBT	46.5	53	0.04	0.01	-	1260°C
CWBT	40.6	49.5	5.50	4.00	-	870°C
CHBT	49.7	35.1	0.04	0.01	14.7	1425°C
Glass Fibre	15.2/ 15.5	53.7/ 57.5	21.1/ 21.8	1.3/ 1.6	-	+ 5.9-6.2% B ₂ O ₃ 0.11-0.12% TiO ₂ 0.46% Na ₂ O 0.32-0.33% K ₂ O
Needled Glass Fibre	3.7	60.5/ 60.0	8.1 7.9	4.0	-	+ 2.85-2.95% B ₂ O ₃ 13.5% Na ₂ O 1.0% K ₂ O

[MST = Maximum Service Temperature (oxidising atmosphere)]

The fibres SW-A, SW-A1, SW-A2, SW-B1, SW-B2 and SW-B3 were tested for solubility by the following method.

The fibre was first chopped in the following manner. 2.5 g of fibre (deshotted by hand) was liquidised with 250 cm³ of distilled water in a domestic Moulinex (Trade Mark) food blender for 20 seconds. The suspension was then transferred to a 500 cm³ plastic beaker and allowed to settle after which as much liquid as possible was decanted and the remaining liquid removed by drying in an oven at 110°C.

The solubility test apparatus comprised a shaking incubator water bath, and the test solution had the following composition:-

<u>Compound</u>	<u>Name</u>	<u>Grams</u>
NaCl	Sodium chloride	6.780
NH ₄ Cl	Ammonium chloride	0.540
NaHCO ₃	Sodium bicarbonate	2.270
Na ₂ HPO ₄ ·H ₂ O	Disodium hydrogen phosphate	0.170
Na ₃ C ₆ H ₅ O ₇ P·2H ₂ O	Sodium citrate dihydrate	0.060
H ₂ NCH ₂ CO ₂ H	Glycine	0.450
H ₂ SO ₄ s.g. 1.84	Sulphuric acid	0.050

The above materials were diluted to 1 litre with distilled water to form a physiological-like saline solution.

0.500 grams ± 0.0003 grams of chopped fibre was weighed into a plastic centrifuge tube and 25 cm³ of the above saline solution added. The fibre and saline solution was shaken well and inserted into the shaking incubator water bath maintained at body temperature (37°C ± 1°C). The shaker speed was set at 20 cycles/minute.

After the desired period (usually 5 hours or 24 hours)

the centrifuge tube was removed and centrifuged at ≈ 4500 revs/minute for approximately 5 minutes. Supernatant liquid was then drawn off using a syringe and hypodermic needle. The needle was then removed from the syringe, air expelled from the syringe, and the liquid passed through a filter (0.45 micron cellulose nitrate membrane filter paper [WCN type from Whatman Labsales Limited]) into a clean plastic bottle. The liquid was then analysed by atomic absorption using a Thermo Jarrell Ash Smith - Hiefje II machine.

The operating conditions were:-

<u>ELEMENT</u>	<u>WAVELENGTH(nm)</u>	<u>BAND WIDTH</u>	<u>CURRENT(MA)</u>	<u>FLAME</u> (Nitrous Oxide + Acetylene)
Al	309.3	1.0	8	Fuel Rich
SiO ₂	251.6	0.3	12	" "
CaO	422.7	1.0	7	Fuel Lean
MgO	285.2	1.0	3	" "

The procedure and standards adopted for determining the above elements were as set out below.

SiO₂ can be determined without dilution up to 250 ppm concentration (1 ppm \equiv 1mg/Litre). Above this concentration an appropriate dilution was made volumetrically. A 0.1% KCl solution (0.1g in 100 cm³) was added to the final dilution to prevent ionic interference. NB If glass apparatus is used, prompt analysis is necessary.

From a stock solution of 1000 ppm pure ignited silica (99.999%) (fused with Na₂CO₃ at 1200°C for 20 minutes in a platinum crucible (0.2500g SiO₂/2g Na₂CO₃) and dissolved in dilute hydrochloric acid (4 molar) made up to 250cm³ with distilled water in a plastic volumetric flask) the following

standards were produced:-

<u>STANDARD</u> (PPM SiO_2)	<u>STOCK SOLUTION</u> (cm^3)
10.0	1.0
20.0	2.0
30.0	3.0
50.0	5.0
100.0	10.0
250.0	25.0

Add 0.1% KCl to each standard before making to 100cm^3 .

Aluminium may be measured directly from the sample without dilution. Standards of 1.0, 5.0 and 10.0 ppm Al may be used. For calibration readings are multiplied by 1.8895 to convert from Al to Al_2O_3 .

A standard Al atomic absorption solution (e.g. BDH 1000 ppm Al) was bought and diluted using an accurate pipette to the desired concentration. 0.1% KCl was added to prevent ionic interference.

Calcium may require dilutions on the sample before determination can be carried out (i.e. x 10 and x 20 dilutions). Dilutions must contain 0.1% KCl.

A standard Ca atomic absorption solution (e.g. BDH 1000 ppm Ca) was diluted with distilled water and an accurate pipette to give standards of 0.5, 4.0 and 10.0 ppm. 0.1% KCl is added to prevent ionic interference. To convert readings obtained from Ca to CaO a factor of 1.4 was used.

Magnesium may require dilutions on the sample before determinations can be made (i.e. x 10 and x 20). Add 0.1% KCl to each dilution. To convert Mg to MgO multiply by 1.658.

A standard Mg atomic absorption solution (e.g. BDH 1000 ppm Mg) was diluted with distilled water and an accurate

pipette to give standards of 0.5, 1.0 and 10.0 ppm Mg. 0.1% KCl was added to prevent ionic interference.

All stock solutions were stored in plastic bottles.

The results of the tests are indicated in Table 2.

TABLE 2

BODY FLUIDS SOLUBILITY
(ppm)

	SiO ₂		CaO		MgO	
	5h	24h	5h	24h	5h	24h
SW-A	98	120	63	56	33	66
SW-A1	83	141	32	70	21	70
SW-A2	130	202	43	73	100	177
SW-B1	58	77	10	38	5	9
SW-B2	64	121	27	55	5	10
SW-B3	138	192	80	46	8	21

Fibres with the best solubility (SW-A2 and SW-B3) were then tested, after annealing at varying temperatures, and compared with the comparative examples of Table 1. The results are shown in Table 3.

It can be seen that for the SW-A2 fibre, with increasing annealing temperature, the silica solubility drops progressively. In contrast the SW-B3 composition shows no loss in solubility up to 800°C and although a reduction in solubility is shown above that temperature it is not as dramatic as for SW-A2. Despite this difference in solubility it is to be noted that only the needled GF fibre shows a

comparable silica solubility and that material melts at 700°C.

TABLE 3

<u>Fibre</u>	<u>Condition</u>	<u>Solubility Analyses</u>					
		<u>CaO(ppm)</u>		<u>MgO(ppm)</u>		<u>SiO₂(ppm)</u>	
		5hrs	24hrs	5hrs	24hrs	5hrs	24hrs
SW-A2	As received	58	37	37	3	89	130
SW-A2	600°C, 48hrs	33	56	27	43	60	108
SW-A2	800°C, 48hrs	35	53	17	30	43	87
SW-A2	1000°C, 48hrs	7	3	3	2	11	21
SW-B3	As received	35	69	7	22	22	100
SW-B3	600°C, 48hrs	61	150	12	22	55	130
SW-B3	800°C, 48hrs	41	90	3	7	24	144
SW-B3	1000°C, 48hrs	18	40	3	3	17	60
CRBT	As received	10	8	6	3	5	3
CHBT	As received	16	10	7	3	4	0.3
Glass Fibre	As received	14	17	5	3	5	7
Needled GF	As received	17	34	8	15	66	85
Needled GF	600°C, 48 hrs	11	26	7	10	19	37
Mineral Fibre	As received	16	16	7	6	8	9

[The Glass Fibre and Needled Glass Fibre had the compositions shown in Table 1.]

The user is primarily concerned with the solubility of the fibre as received as it is in this condition that most handling occurs; as received both SW-A2 and SW-B3 fibres have extremely high solubility. Even after exposure to 800°C and 1000°C these fibres have solubilities much higher than other high temperature use fibres.

To investigate the reasons underlying the difference in solubilities after high temperature annealing between the SW-A2 and SW-B3 fibres qualitative X-ray diffraction was done on the fibres. The results are indicated in Table 4 and it can be seen that the SW-B3 fibre forms pseudowollastonite and wollastonite, whereas the SW-A2 fibre forms diopside. It appears therefore that the crystalline diopside has a lower solubility in physiological saline solution than the crystalline pseudowollastonite and wollastonite material precipitated from the SW-B3 fibre.

TABLE 4

<u>Sample</u>	<u>Condition</u>	<u>Qualitative XRD</u>
SW-A2	600°C, 48 hours	Amorphous
SW-A2	800°C, 48 hours	Amorphous with small amount Diopside
SW-A2	1000°C, 48 hours	Diopside
SW-B3	600°C, 48 hours	Amorphous
SW-B3	800°C, 48 hours	Amorphous
SW-B3	1000°C, 48 hours	Pseudowollastonite & Wollastonite

Various of the fibres were then tested for their shrinkage characteristics. Table 5 shows the results of Shrinkage tests on all the test fibres and on some of the comparative fibres. These results were obtained by proposed ISO standard ISO/TC33/SC2/N220 (equivalent to British Standard

BS 1920, part 6, 1986) with some modifications to account for small sample size. The method in summary comprises the manufacture of vacuum cast preforms, using 75g of fibre in 500cm³ of 0.2% starch solution, into a 120 x 65mm tool. Platinum pins (approx 0.1-0.3mm diameter) were placed 100 x 45mm apart in the 4 corners. The longest lengths (L1 & L2) and the diagonals (L3 & L4) were measured to an accuracy of ± 0.01 mm using a travelling microscope attached to a steel rule with a vernier scale. The samples were placed in a furnace at temperature and left for 24 hours. The shrinkage values are given as an average of the 4 measurements.

TABLE 5

LINEAR SHRINKAGE (%)

(24h at temperature)

Temp. °C	SW-A	SW-A1	SW-A2	SW-B1	SW-B2	SW-B3
730	1.45		1.43	1.02	0.22	
870				0.41		
900			1.07			1.07
1000		1.04	1.3	0.51	0.6	1.1
1100		0.71	1.8		0.73	2.2
Maximum Service Temperature °C	850	1050	1050	1050	1050	1000

It can be seen that in SW-A, SW-A1, SW-A2, SW-B1, SW-B2 and SW-B3, owing to the increase in molar volume on crystallisation, the linear shrinkage at the maximum service temperature is less than 3.5%.

Table 6 shows the results of a further series of shrinkage tests made in the same way.

TABLE 6

Sample	Measurement Direction c.f. Roll Direction	Test Temperatures °C	Linear Shrinkages %	
			Range	Mean
SW-A2	Parallel	850	1.1-1.4	1.2
SW-A2	Perpendicular	850	0.7-1.5	1.3
SW-A2	Parallel	900	0.5-1.1	0.9
SW-A2	Perpendicular	900	1.9-4.5	3.0
SW-A2	Parallel	1000	0.5-2.9	1.3
SW-A2	Perpendicular	1000	1.7-2.9	2.2
SW-A2	Parallel	1100	0.7-1.5	1.0
SW-A2	Perpendicular	1100	1.0-2.6	1.8
SW-B3	Parallel	900	1.6-1.8	1.7
SW-B3	Perpendicular	900	1.4-2.4	2.1
SW-B3	Parallel	1000	1.6-2.3	1.9
SW-B3	Perpendicular	1000	1.0-2.3	1.7
SW-B3	Parallel and Perpendicular	1100	Complete Melting (Lantern type remnant)	

To ascertain the applicability of these tests to long term usage a series of cyclic shrinkage tests were undertaken on the materials and the heating schedule used for these cyclic

tests is shown in Figure 3.

The results of the tests are shown in Tables 7 & 8 (the two figures given for SW-B3 are due to slight differences in chemical analysis [the fibre at the end of a production run of fibre tends to have slightly differing composition to that at the beginning of a production run of fibre]).

As a further comparison with the above discussed materials a melt was made comprising 55% SiO_2 , 29.9% CaO and 18.6% MgO . Fibres made using this composition had a maximum service temperature of 700°C and melted at 800°C.

As these results were encouraging the applicants conducted a further and extensive series of tests, concentrating on the SW-A2 and SW-B3 compositions, to ascertain the reproducibility of these results and the boundaries of the useful compositions.

Table 9 (three pages) below gives the compositions of a series of melts, ranked on silica content, and showing the shrinkage figure after exposure to 1000°C for 24 hours (1st column) and 800°C for 24 hours (2nd column). These shrinkages were measured by the same method as the shrinkages given above but measurements were made with a travelling microscope with a digital linear scale accurate to $\pm 5\mu\text{m}$. It can clearly be seen that all fibres with a silica content of less than 58% have a shrinkage at 1000°C of greater than 3.5% save two (B3-3 and 708). These fibres, together with some fibres with a silica content of greater than 58% although showing a reasonable figure at 1000°C, show a very poor figure at 800°C. Compositions with an SiO_2 content of greater than 70% appear to fiberise poorly. This may be because such compositions have two liquids in the melt as may be appreciated from Fig.1

TABLE 7
CYCLIC SHRINKAGE (LINEAR)

(%)

Product	1000°C	1100°C	24h at 1000°C
No. cycles	58	42	
CRBT	2.0	2.7	1.9
CWBT	15.0	13.3	12.1
SW-A2	0.33	2.0	1.3
SW-B3	1.00	1.67	1.1
SW-B3	0.33	0.67	1.1

Accuracy: + or - 0.33%

TABLE 8
CYCLIC SHRINKAGE

(%)

PRODUCT	LINEAR SHRINKAGE			THICKNESS SHRINKAGE	
	1000°C	1100°C	24 h. at 1000°C	1000°C	1100°C
No. cycles	104	100		104	100
CRBT	1.47	3.1	1.9	0.47	11.19
CWBT	14.4	15.2	12.1	38.63	32.14
SW-A2	1.5	2.1	1.3	8.58	8.75
SW-B3	1.73	1.63	1.1	7.24	7.57
SW-B3	1.47	1.77	1.1	7.02	7.16

Accuracy: + or - 0.3%(%)

TABLE 9

Melt	Analysed Compositions (Weight %)								Shrinkage at °C		Rationalised Compositions		
	SiO ₂ %	CaO%	MgO%	Al ₂ O ₃ %	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	ZrO ₂ %	1000	800	SiO ₂ %	CaO%	MgO%
A2-28	78.07	2.07	17.15	0.15	<0.05	<0.05	0.11	1.76	1		80.3	2.1	17.6
A2-16	73.43	12.40	10.09	0.19	<0.05	<0.05	0.11	2.23	0.7	*	76.6	12.9	10.5
A2-32	73.09	6.36	19.60	0.23	0.05	<0.05	0.11	0.36	1		73.8	6.4	19.8
B3-32	72.38	23.43	0.65	0.31	0.31	0.09	0.22	0.72	1		75.0	24.3	0.7
A2-15	72.25	12.67	12.35	0.11	<0.05	<0.05	0.10	1.24	1.1	*	74.3	13.0	12.7
A2-22	71.48	9.36	16.34	0.33	0.10	<0.05	0.20	0.83	1.1	*	73.6	9.6	16.8
A2-29	71.24	4.46	22.31	0.19	<0.05	<0.05	0.13	1.23	1.8	*1.5	72.7	4.5	22.8
A2-27	71.14	6.77	19.64	0.24	0.08	<0.05	0.13	1.01	1.2	*1.2	72.9	7.0	20.1
B3-28	70.81	18.74	7.03	0.47	0.23	0.07	0.16	0.75	0.2	*	73.3	19.4	7.3
A2-17	70.43	11.58	14.52	0.15	<0.05	<0.05	0.13	1.58	1.3	*	73.0	12.0	15.0
A2-33	70.04	4.61	22.85	0.25	0.11	<0.05	0.12	1.01	1		71.9	4.7	23.4
B3-18	69.42	23.27	3.76	0.43	0.37	0.06	0.12	0.47	0.4		72.0	24.1	3.9
A2-6	69.29	15.17	12.76	0.07	0.25	<0.05	0.11	1.13	1.5		71.3	15.6	13.1
B3-16	68.74	24.99	1.71	0.65	0.38	0.10	0.24	1.03	0.3	0.2	72.0	26.2	1.8
A2-26	68.65	8.12	19.26	0.29	<0.05	<0.05	0.21	0.98	1.5	1.5	71.5	8.4	20.1
B3-27	68.56	20.98	7.00	0.78	0.35	0.08	0.17	0.79	0.8	0.7	71.0	21.7	7.3
759	68.33	17.45	12.60	<0.05	0.11	<0.05	0.33	<0.05	1.7	1.1	69.5	17.7	12.8
A2-20	68.19	11.58	16.57	0.40	0.19	0.05	0.21	0.91	1.1	1.0	70.8	12.0	17.2
A2-31	67.62	8.45	21.72	0.32	0.09	<0.05	0.15	0.64	2.3	1.9	69.2	8.6	22.2
B3-31	67.59	27.76	0.49	0.40	0.40	0.11	0.22	1.01	0.7		70.5	29.0	0.5
B3-19	67.58	24.91	3.65	0.45	0.37	0.07	0.15	0.65	0.5		70.3	25.9	3.8
B3-17	67.25	26.68	1.86	0.70	0.45	0.10	0.23	0.57	0.3		70.2	27.9	1.9
A2-13	66.67	14.87	16.01	0.11	0.05	<0.05	0.10	0.92	1.6		68.4	15.2	16.4
B3-22	66.17	21.28	9.34	0.52	0.33	0.08	0.18	0.54	1.1	0.8	68.4	22.0	9.6
A2-10	66.17	16.22	15.80	0.49	0.06	<0.05	0.09	<0.05	2.2	1.9	67.4	16.5	16.1
B3-15	65.86	29.82	1.78	0.47	0.45	0.08	0.18	0.51	0.3		67.6	30.6	1.8
719	65.77	25.69	8.12	<0.05	0.24	<0.05	0.23	<0.05	0.5		66.0	25.8	8.2
A2-5	65.69	18.74	13.78	0.18	0.16	<0.05	0.10	0.14	1.9	1.0	66.9	19.1	14.0
B3-4A	65.50	25.81	4.88	2.05	0.28	0.12	0.16	0.24	1.4	1.0			
A2-8	65.33	16.86	14.24	0.22	0.13	<0.05	0.14	1.17	1.5		67.7	17.5	14.8

TABLE 9 (continued)

Melt	Analysed Compositions (Weight %)										Shrinkage at °C		Rationalised Compositions		
	SiO ₂ %	CaO%	MgO%	Al ₂ O ₃ %	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	ZrO ₂ %			1000	800	SiO ₂ %	CaO%	MgO%
718	65.23	27.14	6.95	<0.05	0.24	<0.05	0.20	0.49	0.4		0.4		65.7	27.3	7.0
B3-14	65.11	24.91	5.54	0.58	0.43	0.09	0.19	0.61	1.0		1.0		68.1	26.1	5.8
721	65.08	27.26	5.33	0.06	0.17	<0.05	0.08	<0.05	0.3	0.6		0.6	66.6	27.9	5.5
A2-34	64.85	6.63	26.20	0.23	0.06	<0.05	0.16	0.80	3.4	3.9		3.9	66.4	6.8	26.8
A2-21	64.16	13.74	19.98	0.34	0.17	<0.05	0.11	0.13	3.2	3.3		3.3	65.6	14.0	20.4
B3-30	64.13	31.93	0.37	0.64	0.45	0.09	0.14	0.28	0.6				66.5	33.1	0.4
A2-35	64.12	8.88	24.88	0.29	0.10	<0.05	0.13	0.47	7.3	7.1		7.1	65.5	9.1	25.4
B3-23	64.09	23.26	9.33	0.56	0.36	0.09	0.16	0.30	1.0				66.3	24.0	9.7
B3-5A	63.74	25.41	4.68	3.97	0.26	0.12	0.17	0.58	7.4	4.3		4.3			
A2-30	63.68	16.06	18.21	0.40	0.11	0.07	0.15	<0.05	2.7	1.6		1.6	65.0	16.4	18.6
A2-9	63.66	21.44	12.96	1.49	0.32	0.10	0.11	<0.05	1.9	0.9		0.9	64.9	21.9	13.2
A2-12	63.56	16.55	18.00	0.33	0.11	<0.05	0.08	0.05	1.0	2.3		2.3	64.8	16.9	18.3
B3-6A	63.24	24.83	4.59	5.70	0.27	0.11	0.15	0.15	21.6	18.8		18.8			
723	62.61	29.79	5.44	<0.05	0.17	<0.05	0.13	<0.05	0.4	0.5		0.5	64.0	30.4	5.6
757	62.60	20.92	15.22	0.20	<0.05	<0.05	0.16	<0.05	1.3	2.9		2.9	63.4	21.2	15.4
A2-25	62.36	10.99	24.18	0.33	0.10	0.05	0.16	0.07	6.1				63.9	11.3	24.8
B3-13	62.33	30.62	2.06	0.55	0.65	0.09	0.17	0.91	0.8	0.9		0.9	65.6	32.2	2.2
A2-7	61.98	23.37	11.98	0.44	0.25	<0.05	0.10	0.23	1.4				63.7	24.0	12.3
725	61.83	28.13	7.54	0.10	0.36	<0.05	0.17	<0.05	0.6				63.4	28.9	7.7
B3-11	61.71	33.25	2.33	0.69	0.52	0.12	0.25	0.59	0.9				63.4	34.2	2.4
B3-24	61.62	25.53	9.73	0.58	0.38	0.10	0.17	<0.05	1.8	1.2		1.2	63.6	26.4	10.0
A2-24	61.38	13.62	22.74	0.31	0.16	<0.05	0.14	0.08	3.3	12.3		12.3	62.8	13.9	23.3
722	61.33	31.08	5.25	0.05	0.20	<0.05	0.16	<0.05	1.3				62.8	31.8	5.4
924	61.32	19.78	14.54	2.57	<0.05	<0.05	0.09	0.66	0.3	3.0		3.0	64.1	20.7	15.2
B3-2A	60.83	32.30	0.48	4.15	0.35	0.15	0.19	0.12	7.5	3.3		3.3	62.2	25.9	11.9
A2-14	60.74	25.30	11.66	0.28	0.18	0.05	0.13	0.16	1.8						
B3-1A	60.32	32.27	3.99	1.74	0.32	0.10	0.15	0.09	2.5	1.7		1.7	61.7	24.8	13.5
A2-11	60.32	24.28	13.24	0.25	0.18	<0.05	0.09	0.08	1.8	1.1		1.1	62.0	35.4	2.6
B3-9	60.28	34.49	2.50	0.76	0.50	0.13	0.28	0.49	1.6	1.7		1.7	62.0	35.4	2.6
A2-23	60.20	18.59	18.78	0.48	0.19	0.08	0.15	0.05	18.9	10.7		10.7	61.7	19.1	19.2

	Analysed Compositions (Weight %)										Shrinkage at °C		Rationalised Compositions		
	SiO ₂ %	CaO %	MgO %	Al ₂ O ₃ %	Na ₂ O %	K ₂ O %	Fe ₂ O ₃ %	ZrO ₂ %	1000	800	SiO ₂ %	CaO %	MgO %		
Melt															
B3-1	60.11	32.56	3.80	0.79	0.54	0.12	0.23	0.82	0.5		62.3	33.8	3.9		
932	59.85	21.60	15.65	1.50	0.06	<0.05	0.18	0.11	12.8		61.6	22.3	16.1		
692	59.82	34.34	5.44	0.13	0.19	<0.05	0.08	0.17	2.1		60.0	34.5	5.5		
B3-3A	59.54	31.64	0.67	5.91	0.33	0.15	0.21	0.41	43.3	15.3					
B3-25	59.53	28.15	9.22	0.48	0.39	0.08	0.14	<0.05	2.3		61.4	29.1	9.5		
B3-29	59.40	36.00	0.68	0.92	0.43	0.14	0.23	0.17	0.9		61.8	37.5	0.7		
714	59.05	32.00	8.27	<0.05	0.27	<0.05	0.40	<0.05	0.7	1.2	59.5	32.2	8.3		
696	58.81	30.91	6.15	0.21	0.18	<0.05	0.08	0.24	0.3	1.4	61.3	32.3	6.4		
A2-19	58.71	18.48	19.74	0.54	0.20	0.07	0.19	<0.05	4.7		60.6	19.0	20.4		
586	58.65	35.03	3.90	0.13	0.23	<0.05	0.16	<0.05	1.9	1.6	60.1	35.9	4.0		
694	58.39	33.10	6.02	0.27	0.20	<0.05	0.10	0.17	1.6	1.9	59.9	33.9	6.2		
765	57.78	3.90	35.07	2.12	<0.05	<0.05	0.23	<0.05	34.2		59.7	4.0	36.3		
660	57.74	34.65	4.83	1.15	0.24	<0.05	0.19	<0.05	24.7		59.4	35.6	5.0		
B3-20	57.57	32.70	6.07	0.91	0.57	0.13	0.22	<0.05	30.9		59.8	33.9	6.3		
712	57.54	35.39	4.61	0.06	0.23	<0.05	0.12	<0.05	4.4	3.4	59.0	36.3	4.7		
B3-21	57.38	36.62	2.43	0.73	0.51	0.11	0.16	0.08	30.3		59.5	38.0	2.5		
B3-26	56.98	30.50	9.44	0.62	0.44	0.11	<0.05	<0.05	39.8	26.6	58.8	31.5	9.7		
A2-18	56.96	26.29	13.01	0.66	0.51	0.10	0.19	<0.05	36.2		59.2	27.3	13.5		
971	56.82	23.92	17.36	0.74	0.18	<0.05	0.14	0.05	41.7		57.9	24.4	17.7		
734	56.58	23.62	17.05	1.00	0.06	<0.05	0.13	0.05	39.3		58.2	24.3	17.5		
973	56.18	24.45	16.81	0.50	0.08	<0.05	0.14	0.05	34.9		57.7	25.1	17.2		
B3-3	55.99	36.07	4.44	0.58	0.45	0.09	0.38	1.46	0.3	34.7	58.0	37.4	4.6		
708	55.22	42.79	0.77	<0.05	0.31	<0.05	0.12	<0.05	1.1	8.7	55.9	43.3	0.8		
71	54.68	24.04	19.66	0.20	0.17	<0.05	0.23	<0.05	51.7		55.6	24.4	20.0		

*Poor fibres containing a lot of shot. All other constituents $< 0.1\%$.

Too poor to test for solubility or shrinkage

TABLE 10

	Analysed Compositions (Weight %)								Solubilities ppm			Rationalised Compositions		
	SiO ₂ %	CaO%	MgO%	Al ₂ O ₃ %	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	ZrO ₂ %	SiO ₂	CaO	MgO	SiO ₂ %	CaO%	MgO%
Melt	78.07	2.07	17.15	0.15	<0.05	<0.05	0.11	1.76	9	45	55	80.3	2.1	17.6
A2-28	73.43	12.40	10.09	0.19	<0.05	<0.05	0.11	2.23	113			76.6	12.9	10.5
A2-16	73.09	6.36	19.60	0.23	0.05	<0.05	0.11	0.36	9			73.8	6.4	19.8
A2-32	72.38	23.43	0.65	0.31	0.31	0.09	0.22	0.72	9			75.0	24.3	0.7
B3-32	72.25	12.67	12.35	0.11	<0.05	<0.05	0.10	1.24	105	35	48	74.3	13.0	12.7
A2-15	71.48	9.36	16.34	0.33	0.10	<0.05	0.20	0.83	126	36	75	73.6	9.6	16.8
A2-22	71.24	4.46	22.31	0.19	<0.05	<0.05	0.13	1.23	94	21	105	72.7	4.5	22.8
A2-29	71.14	6.77	19.64	0.24	0.08	<0.05	0.13	1.01	101	24	67	72.9	7.0	20.1
B3-28	70.81	18.74	7.03	0.47	0.23	0.07	0.16	0.75	108	49	31	73.3	19.4	7.3
A2-17	70.43	11.58	14.52	0.15	<0.05	<0.05	0.13	1.58	91	35	72	73.0	12.0	15.0
A2-33	70.04	4.61	22.85	0.25	0.11	<0.05	0.12	1.01	9			71.9	4.7	23.4
B3-18	69.42	23.27	3.76	0.43	0.37	0.06	0.12	0.47	145	66	17	72.0	24.1	3.9
A2-6	69.29	15.17	12.76	0.07	0.25	<0.05	0.11	1.13	152	48	70	71.3	15.6	13.1
B3-16	68.74	24.99	1.71	0.65	0.38	0.10	0.24	1.03	132	72	10	72.0	26.2	1.8
A2-26	68.65	8.12	19.26	0.29	<0.05	<0.05	0.21	0.98	183	31	97	71.5	8.4	20.1
B3-27	68.56	20.98	7.00	0.78	0.35	0.08	0.17	0.79	122	54	20	71.0	21.7	7.3
759	68.33	17.45	12.60	<0.05	0.11	<0.05	0.33	<0.05	117	38	40	69.5	17.7	12.8
A2-20	68.19	11.58	16.57	0.40	0.19	0.05	0.21	0.91	162	31	69	70.8	12.0	17.2
A2-31	67.62	8.45	21.72	0.32	0.09	<0.05	0.15	0.64	103	26	72	69.2	8.6	22.2
B3-31	67.59	27.76	0.49	0.40	0.40	0.11	0.22	1.01	112	50	4	70.5	29.0	0.5
B3-19	67.58	24.91	3.65	0.45	0.37	0.07	0.15	0.65	163	44	21	70.3	25.9	3.8
B3-17	67.25	26.68	1.86	0.70	0.45	0.10	0.23	0.57	162	49	13	70.2	27.9	1.9
A2-13	66.67	14.87	16.01	0.11	0.05	<0.05	0.10	0.92	159	47	70	68.4	15.2	16.4
A2-10	66.17	16.22	15.80	0.49	0.06	<0.05	0.09	<0.05	122	42	52	67.4	16.5	16.1
B3-22	66.17	21.28	9.34	0.52	0.33	0.08	0.18	0.54	174	62	57	68.4	22.0	9.6
B3-15	65.86	29.82	1.78	0.47	0.45	0.08	0.18	0.51	156	38	7	67.6	30.6	1.8
B3-15	65.77	25.69	8.12	<0.05	0.24	<0.05	0.23	<0.05	115	51	24	66.0	25.8	8.2
719	65.69	18.74	13.78	0.18	0.16	<0.05	0.10	0.14	150	48	60	66.9	19.1	14.0
A2-5	65.50	25.81	4.88	2.05	0.28	0.12	0.16	0.24	82	52	16			
B3-4A	65.33	16.86	14.24	0.22	0.13	<0.05	0.14	1.17	181	54	84	67.7	17.5	14.8

TABLE 10 (continued)

	Analysed Compositions (Weight %)								Solubilities ppm			Rationalised Compositions		
	SiO ₂ %	CaO%	MgO%	Al ₂ O ₃ %	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	ZrO ₂ %	SiO ₂	CaO	MgO	SiO ₂ %	CaO%	MgO%
Melt														
718	65.23	27.14	6.95	<0.05	0.24	<0.05	0.20	0.49	107	47	20	65.7	27.3	7.0
B3-14	65.11	24.91	5.54	0.58	0.43	0.09	0.19	0.61	158	67	27	68.1	26.1	5.8
721	65.08	27.26	5.33	0.06	0.17	<0.05	0.08	<0.05	153	68	20	66.6	27.9	5.5
A2-34	64.85	6.63	26.20	0.23	0.06	<0.05	0.16	0.80	39	11	119	66.4	6.8	26.8
A2-21	64.16	13.74	19.98	0.34	0.17	<0.05	0.11	0.13	160	28	56	65.6	14.0	20.4
B3-30	64.13	31.93	0.37	0.64	0.45	0.09	0.14	0.28	163	83	3	66.5	33.1	0.4
A2-35	64.12	8.88	24.88	0.29	0.10	<0.05	0.13	0.47	61	18	106	65.5	9.1	25.4
B3-23	64.09	23.26	9.33	0.56	0.36	0.09	0.16	0.30	101	44	31	66.3	24.0	9.7
B3-5A	63.74	25.41	4.68	3.97	0.26	0.12	0.17	0.58	48	43	11			
A2-30	63.68	16.06	18.21	0.40	0.11	0.07	0.15	<0.05	102	33	52	65.0	16.4	18.6
A2-9	63.66	21.44	12.96	1.49	0.32	0.10	0.11	<0.05	195	67	66	64.9	21.9	13.2
A2-12	63.56	16.55	18.00	0.33	0.11	<0.05	0.08	0.05	160	47	66	64.8	16.9	18.3
B3-6A	63.24	24.83	4.59	5.70	0.27	0.11	0.15	0.15	26	7	26			
723	62.61	29.79	5.44	<0.05	0.17	<0.05	0.13	<0.05	141	62	17	64.0	30.4	5.6
757	62.60	20.92	15.22	0.20	<0.05	<0.05	0.16	<0.05	187	62	73	63.4	21.2	15.4
A2-25	62.36	10.99	24.18	0.33	0.10	0.05	0.16	0.07	160	35	105	63.9	11.3	24.8
B3-13	62.33	30.62	2.06	0.55	0.65	0.09	0.17	0.91	151	41	7	65.6	32.2	2.2
A2-7	61.98	23.37	11.98	0.44	0.25	<0.05	0.10	0.23	178	59	63	63.7	24.0	12.3
725	61.83	28.13	7.54	0.10	0.36	<0.05	0.17	<0.05	186	76	35	63.4	28.9	7.7
B3-11	61.71	33.25	2.33	0.69	0.52	0.12	0.25	0.59	162	28	15	63.4	34.2	2.4
B3-24	61.62	25.53	9.73	0.58	0.38	0.10	0.17	<0.05	185	37	57	63.6	26.4	10.0
A2-24	61.38	13.62	22.74	0.31	0.16	<0.05	0.14	0.08	136	27	87	62.8	13.9	23.3
722	61.33	31.08	5.25	0.05	0.20	<0.05	0.16	<0.05	185	81	23	62.8	31.8	5.4
924	61.32	19.78	14.54	2.57	<0.05	<0.05	0.09	0.66	77	36	37	64.1	20.7	15.2
B3-2A	60.83	32.30	0.48	4.15	0.35	0.15	0.19	0.12	58	61	5			
A2-14	60.74	25.30	11.66	0.28	0.18	0.05	0.13	0.16	127	57	43	62.2	25.9	11.9
B3-1A	60.32	32.27	3.99	1.74	0.32	0.10	0.15	0.09	119	72	16			
A2-11	60.32	24.28	13.24	0.25	0.18	<0.05	0.09	0.08	149	54	51	61.7	24.8	13.5
B3-9	60.28	34.49	2.50	0.76	0.50	0.13	0.28	0.49	175	8	5	62.0	35.4	2.6
A2-23	60.20	18.59	18.78	0.48	0.19	0.08	0.15	0.05	192	35	47	61.7	19.1	19.2

TABLE 10 (continued)

	Analysed Compositions (Weight %)								Solubilities ppm			Rationalised Compositions		
	SiO ₂ %	CaO%	MgO%	Al ₂ O ₃ %	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	ZrO ₂ %	SiO ₂	CaO	MgO	SiO ₂ %	CaO%	MgO%
Melt														
B3-1	60.11	32.56	3.80	0.79	0.54	0.12	0.23	0.82	146	84	17	62.3	33.8	3.9
932	59.85	21.60	15.65	1.50	0.06	<0.05	0.18	0.11	92	41	43	61.6	22.3	16.1
692	59.82	34.34	5.44	0.13	0.19	<0.05	0.08	0.17	140	67	23	60.0	34.5	5.5
B3-3A	59.54	31.64	0.67	5.91	0.33	0.15	0.21	0.41	30	25	10			
B3-25	59.53	28.15	9.22	0.48	0.39	0.08	0.14	<0.05	133	48	33	61.4	29.1	9.5
B3-29	59.40	36.00	0.68	0.92	0.43	0.14	0.23	0.17	201	29	5	61.8	37.5	0.7
714	59.05	32.00	8.27	<0.05	0.27	<0.05	0.40	<0.05	142	73	30	59.5	32.2	8.3
696	58.81	30.91	6.15	0.21	0.18	<0.05	0.08	0.24	163	48	37	61.3	32.3	6.4
A2-19	58.71	18.48	19.74	0.54	0.20	0.07	0.19	<0.05	125	42	66	60.6	19.0	20.4
586	58.65	35.03	3.90	0.13	0.23	<0.05	0.16	<0.05	182	54	19	60.1	35.9	4.0
694	58.39	33.10	6.02	0.27	0.20	<0.05	0.10	0.17	133	66	27	59.9	33.9	6.2
765	57.78	3.90	35.07	2.12	<0.05	<0.05	0.23	<0.05	100	16	169	59.7	4.0	36.3
660	57.74	34.65	4.83	1.15	0.24	<0.05	0.19	<0.05	152	69	23	59.4	35.6	5.0
B3-20	57.57	32.70	6.07	0.91	0.57	0.13	0.22	<0.05	181	29	40	59.8	33.9	6.3
712	57.54	35.39	4.61	0.06	0.23	<0.05	0.12	<0.05	160	24	22	59.0	36.3	4.7
B3-21	57.38	36.62	2.43	0.73	0.51	0.11	0.16	0.08	175	25	16	59.5	38.0	2.5
B3-26	56.98	30.50	9.44	0.62	0.44	0.11	<0.05	<0.05	149	64	41	58.8	31.5	9.7
A2-18	56.96	26.29	13.01	0.66	0.51	0.10	0.19	<0.05	161	47	57	59.2	27.3	13.5
971	56.82	23.92	17.36	0.74	0.18	<0.05	0.14	0.05	142	55	73	57.9	24.4	17.7
734	56.58	23.62	17.05	1.00	0.06	<0.05	0.13	0.05	135	52	66	58.2	24.3	17.5
973	56.18	24.45	16.81	0.50	0.08	<0.05	0.14	0.05	102	42	47	57.7	25.1	17.2
B3-3	55.99	36.07	4.44	0.58	0.45	0.09	0.38	1.46	185	14	18	58.0	37.4	4.6
708	55.22	42.79	0.77	<0.05	0.31	<0.05	0.12	<0.05	193	31	2	55.9	43.3	0.8
71	54.68	24.04	19.66	0.20	0.17	<0.05	0.23	<0.05	133	55	62	55.6	24.4	20.0

There are several anomalies, namely compositions B3-6A, A2-25, A2-24, A2-23, B3-2A, B3-3A, A2-19, and 932. All of these have an SiO_2 content of $> 58\%$ but a high shrinkage.

On the assumption that the minimum silica level for satisfactory shrinkage varies with MgO content the applicants have determined that fibres with a silica content (in weight percent) that fail to meet the following expression do not have satisfactory shrinkages at either or both 800°C and 1000°C :-

SiO_2	$>58\%$	- (for $\text{MgO} \leq 10\%$) and
SiO_2	$>58\% + 0.5(\% \text{MgO} - 10)$	- (for $\text{MgO} \geq 10\%$)

The applicants have further found that the Al_2O_3 content is important. From their studies it appears that the maximum Al_2O_3 content lies somewhere between 2.57% and 3.97%. The applicants have found that with increasing alumina levels the first material to crystallise is calcium aluminate and this possibly forms a liquid phase that assists flow and hence shrinkage.

Table 10 shows, for the same compositions as Table 9, 24 hour solubilities for each major constituent. It can be seen that all of the compositions have high solubilities.

As mentioned above use of CaO in forming calcium containing fibres is inconvenient and can be hazardous. The applicants investigated use of mixed oxide materials that would avoid the handling of CaO. A fibre was made by admixture of magnesia with silica and wollastonite (CaSiO_3).

The raw materials used to make the melt comprised:-

Pennine Darlington Heavy Magnesia (#200)

MgO	-	92.60%
CaO	-	1.75%
Fe ₂ O ₃	-	0.04%
SiO ₂	-	0.20%
Cl	-	0.25%
SO ₃	-	0.70%
LOI	-	4.50%

Partek's Finnish Low Iron Wollastonite (#200)
 (U.K. agent - Cornelius Chemical Co., Romford, Essex)

SiO ₂	-	51.80%
CaO	-	44.50%
MgO	-	0.80%
Al ₂ O ₃	-	0.60%
Fe ₂ O ₃	-	0.30%
Na ₂ O	-	0.10%
K ₂ O	-	0.05%
TiO ₂	-	0.05%
S	-	0.02%
MnO	-	0.01%
P	-	0.01%
F	-	0.01%
LOI	-	1.70%

Hepworth Mineral's Redhill T washed silica sand

SiO ₂	-	99.0% min.
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These constituents were mixed as 78.65% Wollastonite; 19.25% SiO₂; and 3.6% MgO. This gave 0.4 - 0.5% of the final melt as Al₂O₃.

It was surprisingly found that in producing a melt using these constituents the current requirements were only two-thirds that for the use of the raw oxides.

Fibre was produced by blowing (although spinning and other methods can be used). 2 runs were performed with different blowing conditions.

Chemical analysis was undertaken by the Analytical Department at the applicant's subsidiary Morgan Materials Technology (hereinafter called M²T) using wet chemical techniques. Fibre diameters were measured using M²T's Galai particle analyser, with shape analysis software. Typically 40,000 fibres were analysed for each run.

The first result of note was the speed of melt reaction when using wollastonite as compared with lime. Also the current was seen to be very stable throughout the growth of the melt. If the current was lost whilst pulling the electrodes apart the current could be restored simply by pushing them back together again. This was not possible with the runs using lime.

Chemical Analysis

	<u>Others</u>	<u>CaO</u>	<u>MgO</u>	<u>Al₂O₃</u>	<u>SiO₂</u>	<u>ZrO₂</u>	<u>Na₂O</u>	<u>Total</u>
Run1	0.7	32.6	3.8	0.8	60.1	0.8	0.5	99.3
Run2	0.7	32.5	3.8	0.8	60.1	0.8	0.6	99.3

Runs 1 and 2 indicate the respective x-ray fluorescence analyses for each run.

Shrinkage Results (1000°C for 24 hours)

	<u>L1</u>	<u>L2</u>	<u>L3</u>	<u>L4</u>	<u>Av.</u>	<u>Std.Dev.</u>
Run 1	0.9	0.2	0.4	0.6	0.5	0.3
Run 2(A)	1.0	-0.2	0.7	0.6	0.5	0.5
Run 2(B)	0.5	0.2	0.0	0.4	0.2	0.2

Solubility Results (ppm)

	<u>CaO</u>	<u>MgO</u>	<u>SiO₂</u>
Run 1(5 hr)	67	10	95
Run 1(24hr)	84	17	146
Run 2(5hr)	39	7	72
Run 2(24hr)	73	17	186

Fibre diameters

	<u>Mean</u>	<u>Median</u>	<u>100%<</u>	<u>%>5μm</u>	<u>%<1μm</u>
Run 1	5.1 μ m	3.4 μ m	30 μ m	33%	13%
Run 2	4.1 μ m	2.7 μ m	25 μ m	25%	19%

Accordingly it appears to be the case that by using what are cheaper ingredients than the pure oxides one can obtain a fibre that has as high a performance as using purer oxides and at much improved energy costs and safety. It is to be noted that this feature of the invention is not limited to saline soluble fibres and any oxide fibre that contains both calcium and silicon can advantageously be made with a calcium silicate, wollastonite being merely an example of such a silicate.

The previous description is directed towards high temperature usage of particular saline soluble fibres. The following is directed towards the prediction and use of saline soluble fibres. A series of fritted glass melts were made of the compositions shown in Tables 11A and 11B and quenched in water. Solubilities of the various components of the quenched melt were measured by the previously described method of atomic absorption. The solubilities were normalised to a specific surface area of 0.25m²/gram of fibre.

The free energy of hydration was calculated by normalising the chemical analysis to 100 weight %; making the assumption that simple silicates (MSiO₃/M₂SiO₃) are present

and calculating the free energy of hydration contribution of each species; and summing to get the total free energy of hydration. The data in Tables 11A & 11B is also presented in Fig.4. It can be seen that the fibres lie on a generally straight line bar four groups of materials that will be explained below.

Table 11 shows in each column the following:-

Fibre reference
 Composition
 Molar ratios
 Moles/100 grams of melt
 Species assumed (see below)
 Calculated free energy of hydration of assumed species
 (kcal/100 grams)(see below)
 Calculated free energy of hydration of assumed species
 (kJ/kg) (see below)
 Solubility data (# indicates not measured [see below])
 Specific surface area
 Normalised solubility data
 log normalised solubility

The base data on which calculation of the free energy of hydration was done is set out in Tables 12 which indicates free energies of hydration taken from the literature in the units kcal/mol and kJ/mol.

Table of Free Energy of Hydration Values for Silicate Melts

TABLE 11

Melt Code	Composition		Moles in 100g	Species	Moles in kg	Free Energy of Hydration (kcal/100g)	Free Energy of Hydration (kJ/kg)	Solubility		S.S.A. m ² /g	Normalized Solubility	Log (norm. solid)
	Oxide	wt. %						Oxide	(g/m)			
CAS10(B) - A	CaO	47.2	0.852	CaSiO ₃	4.51	-7.3	-304.0	CaO	44	0.30	43	1.63
	Al ₂ O ₃	24.5	0.263	Al ₂ O ₃	2.43	0.8	31.6	Al ₂ O ₃	0			
	SiO ₂	27.1	0.451	CaO	4.01	-5.3	-219.7	SiO ₂	7			
	Total	98.8				-11.8	-492.1	Total	51			
CAS10(B) - B	CaO	46.5	0.842	CaSiO ₃	4.79	-7.7	-322.8	CaO	58	0.39	66	1.82
	Al ₂ O ₃	23.7	0.235	Al ₂ O ₃	2.35	0.7	30.6	Al ₂ O ₃	1			
	SiO ₂	28.6	0.479	CaO	3.63	-4.8	-198.9	SiO ₂	44			
	Total	98.6				-11.8	-491.1	Total	103			
CAS10(B) - C	CaO	47.8	0.863	CaSiO ₃	4.56	-7.3	-307.3	CaO	55	0.36	76	1.88
	Al ₂ O ₃	23.9	0.237	Al ₂ O ₃	2.37	0.7	30.8	Al ₂ O ₃	0			
	SiO ₂	27.1	0.456	CaO	4.07	-5.3	-223.0	SiO ₂	55			
	Total	98.8				-11.9	-499.5	Total	110			
CIS(A)	CaO	42.7	0.790	CaSiO ₃	7.07	-11.4	-476.5	CaO	62	0.40	69	1.84
	SiO ₂	12.7	0.165	CaO	0.83	-1.1	-45.5	SiO ₂	0			
	SiO ₂	41.0	0.707	SiO ₂	1.65	2.6	110.4	SiO ₂	49			
	Total	96.4				-9.9	-411.6	Total	111			
SISiO ₃	SiO ₂	63.1	0.622	SrSiO ₃	5.92	-14.4	-606.4	SiO ₂	2	0.37	249	2.40
	SiO ₂	34.9	0.592	SiO ₂	0.30	-0.5	-21.7	SiO ₂	367			
	Total	98.0				-14.9	-628.1	Total	369			
CASiO ₃	CaO	46.1	0.836	CaSiO ₃	8.36	-13.5	-563.5	CaO	41	0.45	163	2.21
	SiO ₂	52.3	0.884	SiO ₂	0.48	0.3	11.2	SiO ₂	253			
	Total	98.4				-13.2	-552.3	Total	294			
MAS(A)	MgO	18.8	0.305	MgSiO ₃	3.05	-8.8	-367.5	MgO	8	0.56	4	0.60
	Al ₂ O ₃	39.7	0.390	Al ₂ O ₃	3.90	1.2	50.7	Al ₂ O ₃	4			
	SiO ₂	41.1	0.687	SiO ₂	3.82	2.1	89.4	SiO ₂	5			
	Total	99.6				-5.5	-227.4	Total	9			
CAS4	CaO	21.0	0.373	CaSiO ₃	3.73	-6.0	-251.4	CaO	11	0.62	8	0.90
	Al ₂ O ₃	35.4	0.345	Al ₂ O ₃	3.45	1.1	44.9	Al ₂ O ₃	4			
	SiO ₂	44.2	0.731	SiO ₂	7.31	2.0	171.1	SiO ₂	5			
	Total	100.6				-2.9	-35.4	Total	20			
MAS(B)	MgO	10.0	0.256	MgSiO ₃	2.56	-3.6	-149.0	MgO	7	0.52	6	0.78
	Al ₂ O ₃	33.7	0.342	Al ₂ O ₃	3.42	1.1	44.5	Al ₂ O ₃	2			
	SiO ₂	53.0	0.912	SiO ₂	6.56	3.7	153.5	SiO ₂	4			
	Total	96.7				1.2	49.0	Total	13			
SAS(A)	SrO	29.8	0.294	SrSiO ₃	2.94	-7.2	-300.2	SrO	9	0.50	8	0.90
	Al ₂ O ₃	31.1	0.312	Al ₂ O ₃	3.12	1.0	40.6	Al ₂ O ₃	2			
	SiO ₂	36.8	0.627	SiO ₂	3.33	1.9	77.9	SiO ₂	5			
	Total	97.7				-4.3	-181.7	Total	16			
SCS(A)	SrO	35.0	0.339	SrSiO ₃	3.39	-8.3	-346.1	SrO	75	0.41	280	2.45
	CaO	21.0	0.376	CaSiO ₃	3.76	-6.1	-253.4	CaO	30			
	SiO ₂	43.6	0.729	SiO ₂	0.14	0.1	3.3	SiO ₂	355			
	Total	99.6				-14.3	-596.2	Total	440			

Table of Free Energy of Hydration Values for Silicate Melts

TABLE 11 Continued

Melt Code	Composition		Moles in 100g	Species	Moles in kg	Free Energy of Hydration (kcal/100g)		Free Energy of Hydration (kJ/kg)	Solubility (g/cm ³)		S.S.A. (wt%)	Normalized Solubility	Log (molar solubility)
	Oxide	wt. %				Hydrate	Hydrate		Oxide	Hydrate			
SMAS(A)	SrO	55.0	0.546	SrSiO ₃	2.96	-7.2	-302.2	-302.2	SrO	57	0.46	38	1.58
	MgO	1.2	0.030	MgO	0.30	-0.2	-8.2	-8.2	MgO	2			
	Al ₂ O ₃	23.7	0.239	Al ₂ O ₃	2.39	0.7	31.1	31.1	Al ₂ O ₃	5			
	SiO ₂	17.3	0.296	SrO	2.50	-4.3	-181.0	-181.0	SiO ₂	5			
	Total	97.2	100.0			-11.0	-460.3	-460.3	Total	69			
SMAS(B)	SrO	55.0	0.539	SrSiO ₃	4.01	-9.8	-409.4	-409.4	SrO	110	0.39	95	1.98
	MgO	4.8	0.122	MgO	1.22	-0.8	-33.2	-33.2	MgO	15			
	Al ₂ O ₃	16.8	0.148	Al ₂ O ₃	1.48	0.5	19.2	19.2	Al ₂ O ₃	1			
	SiO ₂	23.7	0.401	SrO	1.38	-2.4	-99.9	-99.9	SiO ₂	22			
	Total	98.3	100.0			-12.5	-523.3	-523.3	Total	148			
SHS(A)	SrO	33.0	0.318	SrSiO ₃	3.18	-7.8	-324.7	-324.7	SrO	147	0.39	212	2.35
	MgO	12.5	0.310	MgSiO ₃	3.10	-4.3	-180.4	-180.4	MgO	61			
	Al ₂ O ₃	1.0	0.010	Al ₂ O ₃	0.10	0.0	1.3	1.3	Al ₂ O ₃	0			
	SiO ₂	53.8	0.892	SiO ₂	2.64	1.5	61.8	61.8	SiO ₂	125			
	Total	100.3	100.0			-10.6	-442.0	-442.0	Total	331			
SAS(C)	SrO	56.0	0.562	SrSiO ₃	4.01	-9.8	-409.4	-409.4	SrO	70	0.38	52	1.72
	Al ₂ O ₃	19.7	0.193	Al ₂ O ₃	1.93	0.6	25.1	25.1	Al ₂ O ₃	1			
	SiO ₂	24.0	0.401	SrO	1.41	-2.4	-102.1	-102.1	SiO ₂	8			
	Total	99.7	100.0			-11.6	-486.4	-486.4	Total	79			
	CaO	35.0	0.617	CaSiO ₃	2.93	-4.7	-197.5	-197.5	CaO	11	0.30	24	1.38
CMAS(A)	MgO	4.5	0.109	MgO	1.09	-0.7	-29.6	-29.6	MgO	7			
	Al ₂ O ₃	44.0	0.426	Al ₂ O ₃	4.26	1.5	55.4	55.4	Al ₂ O ₃	3			
	SiO ₂	17.8	0.293	CaO	3.24	-4.2	-177.6	-177.6	SiO ₂	8			
	Total	101.3	100.0			-8.3	-369.3	-369.3	Total	29			
	CaO	21.7	0.387	CaSiO ₃	3.87	-6.2	-260.8	-260.8	CaO	53	0.48	119	2.08
SAS(D)	MgO	15.7	0.389	MgSiO ₃	3.89	-5.4	-226.4	-226.4	MgO	57			
	Al ₂ O ₃	0.8	0.008	Al ₂ O ₃	0.08	0.0	1.0	1.0	Al ₂ O ₃	0			
	SiO ₂	61.8	1.028	SiO ₂	2.52	1.4	59.0	59.0	SiO ₂	118			
	Total	100.0	100.0			-10.2	-427.2	-427.2	Total	228			
	SrO	56.5	0.553	SrSiO ₃	4.13	-10.1	-421.7	-421.7	SrO	107	0.40	92	1.96
KMAS(A)	Al ₂ O ₃	17.6	0.176	Al ₂ O ₃	1.76	0.5	22.9	22.9	Al ₂ O ₃	1			
	SiO ₂	24.4	0.413	SrO	1.40	-2.4	-101.4	-101.4	SiO ₂	39			
	Total	98.5	100.0			-12.0	-500.2	-500.2	Total	147			
	K ₂ O	16.5	0.175	K ₂ SiO ₃	1.75	-7.3	-305.4	-305.4	K ₂ O	8	0.36	14	1.15
	MgO	13.0	0.323	MgSiO ₃	3.23	-2.1	-108.0	-108.0	MgO	8			
	Al ₂ O ₃	18.0	0.176	Al ₂ O ₃	1.76	0.5	22.9	22.9	Al ₂ O ₃	1			
	SiO ₂	52.8	0.875	SiO ₂	6.75	2.1	204.8	204.8	SiO ₂	11			
	Total	100.3	100.0			-6.8	-265.7	-265.7	Total	20			

TABLE 12

<u>Relevant oxides</u>	G_{hyd}	
	(kcal/mole)	(kJ/mol)
$\text{SiO}_2 + \text{H}_2\text{O} \longrightarrow \text{H}_2\text{SiO}_3$ (vitreous silica)	5.6	23.4
$\text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} \longrightarrow 2\text{Al}(\text{OH})_3$	3.1	13.0
$\text{MgO} + \text{H}_2\text{O} \longrightarrow \text{Mg}(\text{OH})_2$	-6.5	-27.2
$\text{CaO} + \text{H}_2\text{O} \longrightarrow \text{Ca}(\text{OH})_2$	-13.1	-54.8
$\text{SrO} + \text{H}_2\text{O} \longrightarrow \text{Sr}(\text{OH})_2$	-17.3	-72.4
$\text{Na}_2\text{O} + \text{H}_2\text{O} \longrightarrow 2\text{NaOH}$	-33.5	-140.2
$\text{K}_2\text{O} + \text{H}_2\text{O} \longrightarrow 2\text{KOH}$	-46.1	-192.9
$\text{TiO}_2 + \text{H}_2\text{O} \longrightarrow \text{Ti}(\text{OH})_2\text{O}$	16.0	66.9
$\text{P}_2\text{O}_5 + 3\text{H}_2\text{O} \longrightarrow 2\text{H}_3\text{PO}_4$	-55.9	-233.9
$\text{B}_2\text{O}_3 + 3\text{H}_2\text{O} \longrightarrow 2\text{H}_3\text{BO}_3$	-9.8	-41.0
$\text{ZrO}_2 + \text{H}_2\text{O} \longrightarrow \text{Zr}(\text{OH})_2\text{O}$	-7.1	-29.7

Relevant Silicates

$\text{Na}_2\text{SiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + 2\text{Na}^+(\text{aq})$	-28.8	-120.5
$\text{K}_2\text{SiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + 2\text{K}^+(\text{aq})$	-41.7	-174.5
$\text{MgSiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + \text{Mg}^{2+}(\text{aq})$	-13.9	-58.2
$\text{CaSiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + \text{Ca}^{2+}(\text{aq})$	-16.1	-67.4
$\text{SrSiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + \text{Sr}^{2+}(\text{aq})$	-24.4	-102.1
$\text{BaSiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + \text{Ba}^{2+}(\text{aq})$	-37.3	-156.1
$\text{ZnSiO}_3 + 2\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + \text{Zn}^{2+}(\text{aq})$	-2.4	-10.0

Disilicates

$\text{Ca}_2\text{SiO}_4 + 3\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + 2\text{Ca}^{2+} + \text{OH}^-$	-30.3	-126.8
$\text{Sr}_2\text{SiO}_4 + 3\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + 2\text{Sr}^{2+} + \text{OH}^-$	-50.3	-210.5
$\text{Mg}_2\text{SiO}_4 + 3\text{H}^+(\text{aq}) \longrightarrow \text{H}_2\text{SiO}_3 + 2\text{Mg}^{2+} + \text{OH}^-$	-17.9	-74.9

Although calculations were undertaken assuming the presence of the simplest silicates choice of other silicates (such as disilicates) does not appear to change the calculations much. For example given below is the calculation for an assumed composition which shows only minor differences for the free energy of hydration calculated.

Composition (moles/100g)	0.767 CaO				
	0.417 MgO				
	0.669 SiO ₂				
0.384 Ca ₂ SiO ₄	=	-11.6	or	0.433 CaSiO ₃	= -7.0
0.285 MgSiO ₃	=	- 4.0		0.236 MgSiO ₃	= -3.3
0.132 MgO	=	- <u>0.9</u>		0.334 CaO	= -4.4
		-16.5		0.181 MgO	= - <u>1.2</u>
					-15.9
			or	0.384 Ca ₂ SiO ₄	= -11.6
				0.132 Mg ₂ SiO ₄	= - 2.4
				0.153 MgSiO ₃	= - <u>2.1</u>
					-16.1

The applicants have found that when the free energy of hydration is more negative than -10kcal/100 grams (-418.4kJ/kg) of composition the composition showed high solubility. The compositions where this relationship broke down were those for which the total solubility was not available (for example those materials containing sodium, where any dissolved sodium would be swamped by the sodium in the saline solution) or where the free energy of hydration of the most likely species present was not available from the literature.

As a test of this technique the two examples of European Patent No. 0399320 were examined. The disclosed examples had the compositions:-

<u>Component</u>	<u>Composition 1</u>	<u>Composition 2</u>
	<u>Weight percent</u>	<u>Weight percent</u>
SiO ₂	60.7	58.5
Al ₂ O ₃	-	5.8
CaO	16.5	3.0
MgO	3.2	-
B ₂ O ₃	3.3	11.0
Na ₂ O	15.4	9.8
K ₂ O	0.7	2.9
Iron oxide	0.2	0.1
BaO	-	5.0
ZnO	-	3.9

Using the above method of calculation Composition 1 had a free energy of hydration of -11.6kcal/100grams (-485.3kJ/kg) whereas Composition 2 had a free energy of hydration of -5.8kcal/100grams (-242.6kJ/kg). This would suggest that Composition 1 would be a saline soluble fibre, and hence physiologically safer than an insoluble fibre; whereas Composition 2 would be predicted to be a relatively insoluble fibre and hence less safe. This is what is disclosed in EP 0399320, the fibres of Composition 2 having a longer lifetime in studies in which the fibres were introduced interperitoneally into rats.

As mentioned above this predictive test can fail under some circumstances. To avoid these difficulties the applicants looked to a different predictive technique, namely the assessment of the amount of non-bridging oxygens present. This is calculated by normalising the chemical analysis to 100 weight%; calculating the molar percentage of each oxide; summing the oxygen-weighted contribution of each oxide to get the total number of oxygens; summing the weighted contribution of each oxide of non-bridging oxygens (see below); and taking the ratio of non-bridging oxygens to the total number of oxygens. The applicants have found that when this figure exceeds 30% the fibres are soluble.

To explain the term non-bridging oxygen one must look to the structure of glasses. Glasses are very stiff liquids and to form usually require the presence of a material that can form a network (usually an oxygen-bridged network). The network may be modified by constituents that contribute non-bridging parts to the network and open the structure of the network and so prevent crystallisation. These materials are usually referred to as network-formers and modifiers respectively.

The terms modifier and network former are well known in the glass industries. Network formers are materials such as SiO_2 , P_2O_5 , B_2O_3 and GeO_2 which can form an interconnected network to form the glassy phase. Modifiers are substances such as CaO , Na_2O , and K_2O which alter the network and have effects on such properties as viscosity and melting point. There are some intermediate materials (such as Al_2O_3 , TiO_2 , PbO , ZnO and BeO) which can act as both network formers and modifiers depending on the environment and on the amount present.

In the above mentioned test, for calculating the non-bridging oxygens, one ignores the network formers and calculates the contribution of each other oxide. The contribution of each oxide depends on the geometry and charge of each cation in the glass. As examples typical contributions are as follows:-

Ca^{2+} , Mg^{2+} , Sr^{2+} and other divalent network modifier cations contribute 2 non-bridging oxygens

K^+ , Na^+ and other monovalent network modifier cations contribute 1 non-bridging oxygen

Al^{3+} , Ti^{3+} and other intermediate cations contribute -1 non-bridging oxygen (i.e these oxides reduce the number of non-bridging oxygens)

(Ti^{4+} is reduced to Ti^{3+} in most glasses when present in relatively small quantities)

TABLE 13

Melt Code	Composition		Moles	Mol. %	Oxygen Total	M.B.O.	Zn.B.O.	Solubility		S.S.-A m ² /g	Normalized Solubility	Log(norm solid)
	Oxide	Wt. %						Oxide	(ppm)			
CAS10(B) - A	CaO	47.2	0.842	54.9	160.8	78.4	48.8	CaO	44	0.30	43	1.63
	Al ₂ O ₃	26.5	0.240	15.7				Al ₂ O ₃	0			
	SiO ₂	27.1	0.451	29.4				SiO ₂	7			
	Total		1.533	100.0				Total	51			
CAS10(B) - B	CaO	46.5	0.829	54.0	160.9	77.8	48.4	CaO	58	0.39	66	1.82
	Al ₂ O ₃	23.7	0.232	15.1				Al ₂ O ₃	1			
	SiO ₂	28.4	0.473	30.8				SiO ₂	44			
	Total		1.534	100.0				Total	103			
CAS10(B) - C	CaO	47.8	0.852	55.4	159.6	80.4	50.4	CaO	55	0.36	76	1.88
	Al ₂ O ₃	23.9	0.234	15.2				Al ₂ O ₃	0			
	SiO ₂	27.1	0.451	29.3				SiO ₂	55			
	Total		1.537	100.0				Total	110			
CIS(A)	CaO	42.7	0.761	47.5	152.5	85.1	55.8	CaO	62	0.40	69	1.84
	SiO ₂	12.7	0.159	9.9				SiO ₂	0			
	SiO ₂	41.0	0.682	42.6				SiO ₂	49			
	Total		1.602	100.0				Total	111			
SrSiO ₃	SrO	63.1	0.609	51.2	148.8	102.4	68.8	SrO	2	0.37	249	2.40
	SiO ₂	34.9	0.581	48.8				SiO ₂	367			
	Total		1.190	100.0				Total	369			
CaSiO ₃	CaO	46.1	0.822	48.6	151.4	97.2	64.2	CaO	41	0.45	163	2.21
	SiO ₂	52.3	0.870	51.4				SiO ₂	253			
	Total		1.692	100.0				Total	294			
MAS(A)	Na ₂ O	18.8	0.303	22.0	228.3	-12.6	-5.5	Na ₂ O	4	0.56	4	0.60
	Al ₂ O ₃	39.7	0.389	28.3				Al ₂ O ₃	4			
	SiO ₂	41.1	0.684	49.7				SiO ₂	5			
	Total		1.376	100.0				Total	9			
CAS4	CaO	21.0	0.374	25.7	198.1	3.8	1.9	CaO	11	0.62	8	0.90
	Al ₂ O ₃	35.4	0.347	23.8				Al ₂ O ₃	4			
	SiO ₂	44.2	0.736	50.5				SiO ₂	5			
	Total		1.457	100.0				Total	20			
MAS(B)	MgO	10.0	0.248	17.0	205.6	-11.2	-5.4	MgO	7	0.52	6	0.78
	Al ₂ O ₃	33.7	0.331	22.6				Al ₂ O ₃	2			
	SiO ₂	53.0	0.882	60.4				SiO ₂	4			
	Total		1.461	100.0				Total	13			
SAS(A)	SrO	29.8	0.288	23.9	201.4	-2.6	-1.4	SrO	9	0.50	8	0.90
	Al ₂ O ₃	31.1	0.305	25.3				Al ₂ O ₃	2			
	SiO ₂	36.8	0.612	50.8				SiO ₂	5			
	Total		1.205	100.0				Total	16			
SCS(A)	SrO	35.0	0.338	23.5	150.5	99.0	65.8	SrO	75	0.41	280	2.45
	CaO	21.0	0.374	26.0				CaO	30			
	SiO ₂	43.6	0.726	50.5				SiO ₂	355			
	Total		1.438	100.0				Total	460			

TABLE 13 (continued)

Melt Code	Composition		Moles	Mol. %	Oxygen Total	M. B. O.	2M. B. O.	Solubility		S. S. A m ² /g	Normalized Solubility	Log(norm solub)
	Oxide	Wt. %						Oxide	(g/m ²)			
SMAS(A)	SrO	55.0	0.531	49.1	169.6	60.8	35.8	SrO	57	0.46	38	1.58
	MgO	1.2	0.030	2.8				MgO	5			
	Al ₂ O ₃	23.7	0.232	21.5				Al ₂ O ₃	2			
	SiO ₂	17.3	0.288	26.6				SiO ₂	5			
	Total		1.081	100.0				Total	69			
SMAS(B)	SrO	55.0	0.531	44.6	157.6	84.8	53.8	SrO	110	0.39	95	1.98
	MgO	4.8	0.119	10.0				MgO	15			
	Al ₂ O ₃	14.8	0.145	12.2				Al ₂ O ₃	1			
	SiO ₂	23.7	0.394	33.2				SiO ₂	22			
	Total		1.189	100.0				Total	148			
SMS(A)	SrO	33.0	0.318	20.7	159.5	80.6	50.5	SrO	147	0.39	212	2.33
	MgO	12.5	0.310	20.2				MgO	61			
	Al ₂ O ₃	1.0	0.010	0.6				Al ₂ O ₃	0			
	SiO ₂	53.8	0.895	58.4				SiO ₂	123			
	Total		1.533	100.0				Total	331			
SAS(C)	SrO	56.0	0.540	47.7	169.3	61.4	36.3	SrO	70	0.38	52	1.72
	Al ₂ O ₃	19.7	0.193	17.0				Al ₂ O ₃	1			
	SiO ₂	24.0	0.399	35.3				SiO ₂	8			
	Total		1.132	100.0				Total	79			
CMAS(A)	CaO	35.0	0.624	42.6	179.3	41.4	23.1	CaO	11	0.30	24	1.38
	MgO	4.5	0.112	7.6				MgO	7			
	Al ₂ O ₃	44.0	0.432	29.5				Al ₂ O ₃	3			
	SiO ₂	17.8	0.296	20.3				SiO ₂	8			
	Total		1.464	100.0				Total	29			
SWA2	CaO	21.7	0.387	21.4	157.5	85.0	54.0	CaO	53	0.48	119	2.08
	MgO	15.7	0.389	21.5				MgO	57			
	Al ₂ O ₃	0.8	0.008	0.4				Al ₂ O ₃	0			
	SiO ₂	61.8	1.028	56.7				SiO ₂	118			
	Total		1.812	100.0				Total	228			
SAS(D)	SrO	56.5	0.545	48.5	166.9	66.2	39.7	SrO	107	0.40	92	1.96
	Al ₂ O ₃	17.6	0.173	15.4				Al ₂ O ₃	1			
	SiO ₂	24.4	0.406	36.1				SiO ₂	39			
	Total		1.124	100.0				Total	147			
KMAS(A)	K ₂ O	16.5	0.175	11.3	179.5	41.4	23.1	K ₂ O	8	0.36	14	1.15
	MgO	13.0	0.323	20.8				MgO	8			
	Al ₂ O ₃	18.0	0.177	11.4				Al ₂ O ₃	1			
	SiO ₂	52.8	0.879	56.6				SiO ₂	11			
	Total		1.554	100.0				Total	20			

Table 13 shows, for the compositions of Table 11, the calculated figure for non-bonding oxygens and these figures are reproduced in Fig.5. It can be seen that the plot of Fig.5 is more linear than that of Fig.4. Compositions with greater than 30% non-bridging oxygens show high solubility.

To illustrate the method the calculation for one example (the first shown in Table 13) is given below:-

	<u>Mols/</u> <u>Mol</u>	<u>Total</u> <u>Oxygen</u>	<u>Non-bridging</u> <u>Oxygens</u>
CaO	0.549	0.549	1.098 (2*0.549)
Al ₂ O ₃	0.157	0.471 (0.157*3)	-0.314 (-1*0.157*2Al)
SiO ₂	0.294	0.588	0.000
	<hr/> 1.000	<hr/> 1.608	<hr/> 0.784

$$\% \text{ non-bridging oxygens } (0.784/1.608)*100 = 48.8\%$$

As an example one can look to European Patent Specification No. 0399320 referred to above. Using this method in relation to that specification Composition 1 has a non-bridging oxygen percentage of 48.2% whereas Composition 2 has a non-bridging oxygen percentage of 19.6%, again predicting that Composition 1 is more soluble than Composition 2.

There is a further criterion which a composition must meet for it to form vitreous fibres, namely that it be capable of forming a glass. The applicants have found a simple test. If the ratio of modifiers to network formers is less than a critical value (for SiO₂ based glasses, 1) the composition will generally form a glass. For the purpose of this test reasonable results are obtained if such intermediate materials are treated as networkers. Table 14 shows for a series of compositions in each column:-

Fibre reference (N.B. these are not the same fibres as shown in tables 9 & 10)

Composition

Molar ratios

Ratio of glass modifiers to network formers

Free energy of hydration of raw oxides

Melting Point

X-ray diffraction results

Solubility data (# indicates not measured)

Specific surface area

Normalised solubility data

Arbitrary ranking as to solubility and glass forming ability

Indication as to whether melting point above 1500°C

It should be emphasised that this test is a screening one rather than a wholly predictive one as there are several circumstances that may lead to its failure. Among these circumstances are compound formation and inability to quench fast enough to form glass.

Having adopted these tests as a screening method there follows a further step to ascertain whether the composition will form a vitreous fibre. This last step is best examined experimentally as fibre forming ability is a complex function of many physical characteristics, e.g. viscosity, which are often difficult to measure.

Key to Fig.1

CR Cristobalite

TR Tridymite

PS Pseudowollastonite

WO Wollastonite

RA Rankinite

LI Lime

PE Periclase

FO Forsterite

PR Protoenstatite

DI Diopside

AK Akermanite

ME Merwinite

MO Monticellite

TABLE 14

[illegible]

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TABLE 14 (continued)

Reference	Composition (wt. %)	Polar Ratios	Modiller? Networker	Chyd (kcal/mol)	M.P.C. (°C)	RD Data	Species	Solubility Data (g/100g)	5 days	Total	S.S.A. (m ² /g)	Norm Solub (0.25 m ² /g)	Criteria (0.70 Rating)	M.P.
SCS(C) No. 36	19.5 SiO ₂ 29.4 CaO 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-3.1 (Eut.)	1500 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(B) No. 39	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-4.6 (Eut.)	1500 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(C) No. 40	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-6.6 (7)	1600 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 41	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-6.6 (7)	1600 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 42	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-6.2 (1560 C)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 43	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-5.0 (1500 C)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 44	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-0.4 (1500 C)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 45	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-5.9 (7)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 46	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-17.7 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 47	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-3.2 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 48	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-10.7 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 49	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-0.2 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 50	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-6.1 (7)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 51	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-2.4 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500
SCS(A) No. 52	19.7 SiO ₂ 29.7 SiO ₂ 47.1 SiO ₂ 5.1 SiO ₂	0.5 SiO ₂ 1.4 CaO 2.1 SiO ₂ 0.5 SiO ₂	U.V.	-6.3 (Eut.)	1610 (Eut.)	Amorphous (No peaks)	SiO ₂ CaO SiO ₂ SiO ₂	36 320 5 5	11 558 10 579	0.82	155	210	10	1500